

(19) World Intellectual Property Organization
International Bureau(43) International Publication Date
21 February 2002 (21.02.2002)

PCT

(10) International Publication Number
WO 02/15450 A1(51) International Patent Classification⁷: H04J 14/02,
H04B 10/18

(21) International Application Number: PCT/IB01/01709

(22) International Filing Date: 2 August 2001 (02.08.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
TO2000A000809 18 August 2000 (18.08.2000) IT(71) Applicant (for all designated States except US): MAR-
CONI COMMUNICATIONS S.P.A. [IT/IT]; Via A Ne-
grone, 1/A, I-16153 Genoa (IT).

(72) Inventors; and

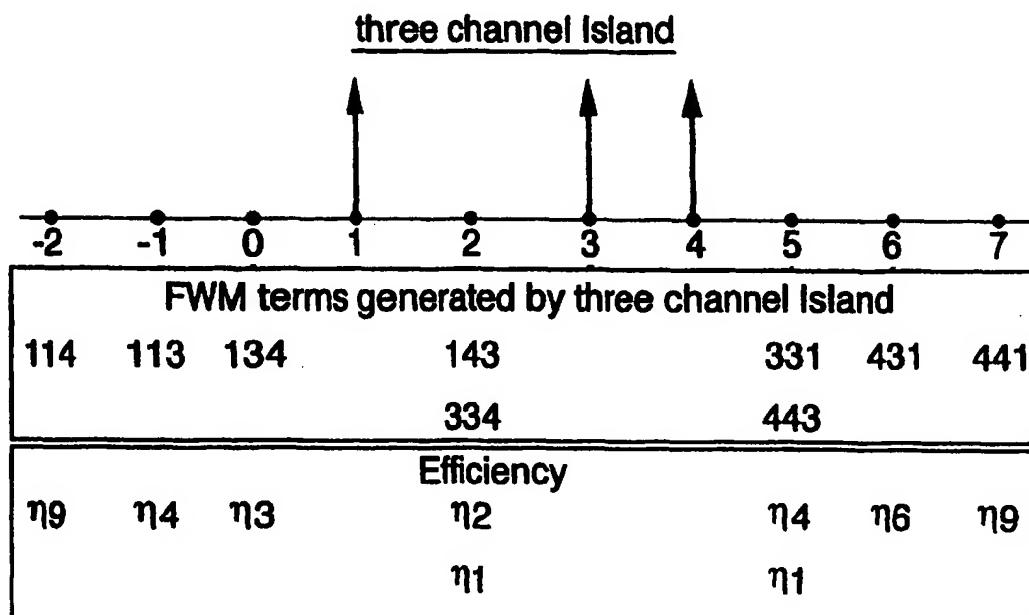
(75) Inventors/Applicants (for US only): POTI, Luca [IT];
Via Navetta, 10, I-43100 Parma (IT). BOGONI, Antonella
[IT]; Via Conciliazione, 61, I-46100 Mantova (IT).(74) Agent: HOSTE, Colin, Francis; Marconi Intellectual
Property, Marrable House, The Vineyards, Gt. Baddow,
Chelmsford, Essex CM2 7QS (GB).(81) Designated States (*national*): AE, AG, AL, AM, AT, AU,
AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU,
CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH,
GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC,
LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW,
MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK,
SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA,
ZW.(84) Designated States (*regional*): ARIPO patent (GH, GM,
KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian
patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European
patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE,
IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF,
CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD,
TG).

Published:

- with international search report
- before the expiration of the time limit for amending the
claims and to be republished in the event of receipt of
amendments
- with (an) indication(s) in relation to deposited biological
material furnished under Rule 13bis separately from the
description

[Continued on next page]

(54) Title: OPTICAL TRANSMISSION SYSTEM



(57) Abstract: A device wavelength division multiplex optical transmission system has the wavelengths of the optical carriers arranged so as to reduce the effect of in-band crosstalk which results from unwanted side bands to the carriers. Possible wavelengths are placed on an equally spaced wavelength grid, and the transmitted channels are organised into groups of three each of which is placed on four adjacent grid positions, one of which is unused. Adjacent groups are spaced apart by two or more vacant grid positions.



For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

Optical Transmission System

This invention relates to an optical transmission system, and more particularly to such a system in which light is transmitted over a single optical fibre at a number, possibly a large number, of different wavelengths, with each wavelength, or 'colour' of light carrying a separate optical communication channel. Such a system is often referred to
5 as a Dense Wavelength Division Multiplex (DWDM) system. One of the effects of fibre transmission characteristics, such as non-linearity, is to degrade the shape of pulses of light transmitted within each channel and to generate undesirable side bands at wavelengths which could differ from the wavelength which is launched at the beginning of a fibre. These side bands can coincide with adjacent transmitted wavelengths (ie
10 slightly different colours) and so interfere with adjacent channels to cause corruption of the pulses transmitted at these other wavelengths.

It is necessary to minimise the channel spacing in DWDM systems so as to accommodate a large number of channels in the available overall bandwidth. In order
15 to maximise the use of the available bandwidth, equal channel spacing on a grid specified by the ITU is frequently adopted, but equal channel spacing is sensitive to unwanted side bands as these can appear as in-band crosstalk disturbances that reduce the signal to crosstalk ratio.

20 The suppression of all in-band crosstalk terms implies an unequal channel spacing allocation that requires a prohibitively large system bandwidth.

The present invention seeks to provide an improved optical transmission system.

According to this invention, an optical transmission system includes an optical transmitter and an optical fibre, the transmitter being arranged to transmit along the
5 fibre a plurality of optical channels each at a different wavelength placed on an equally spaced wavelength grid, the channels being organised into groups of three, each of which is placed on four adjacent grid positions, one position of which is unused, with adjacent groups being spaced apart from each other by two or more vacant grid positions.

10

The invention is further described by way of example with reference to the accompanying drawings, in which:

Figure 1 shows an optical transmission system and

Figures 2, 3 and 4 are explanatory diagrams relating thereto.

15

Referring to Figure 1, an optical transmission system includes an optical transmitter 1 which sends optical communication signals over an optical fibre 2 to an optical receiver 3. The fibre 2 typically can be in excess of 100 kilometres in length, and carries a large number of different communication channels, each at a different wavelength, or colour.
20 Such a system is known as a DWDM system in view of the large number, typically thirtytwo or more, of wavelengths used. The individual thirtytwo communication channels 5 are received at the transmitter 1, and multiplexed together in DWDM for transmission over the single fibre 2 to the receiver 3, where the individual channels 6 are made available at output ports.

In this example, the optical fibre is a non-zero dispersion fibre (NZDSF), and high input channel powers induce non-linear phenomena but degrading the pulse shape. Such a fibre generates what is termed four wave mixing (FWM), which represents undesirable side bands.

Unwanted side bands can also be generated by so-called zero-dispersion fibre.

The optical fibre 2 has an available bandwidth, and there are predetermined discrete wavelengths which can be used for the different channels. These discrete wavelengths correspond to an equal-spaced grid which is specified by the ITU, and the use of an equal channel spacing gives rise to four wave mixing components which causes in-band crosstalk disturbances. The invention substantially reduces this difficulty by the use of a three channel code (TCC) which is represented diagrammatically in Figure 2.

15

In this figure, a standard ITU equal channel spacing grid is shown on the wavelength λ axis, but the optical channels are organised into groups of three wavelengths, of which three such groups 7, 8, 9 are shown. Each group occupies four grid positions, so that one grid position within each group is vacant and the first and last grid positions in each group are occupied. As many groups are provided as is required for the total number of channels to be transmitted. Each group is separated from its adjacent group by two or more vacant grid positions k . In Figure 2, $k = 2$, as there are two vacant grid positions between adjacent groups. In order to make efficient use of the available bandwidth, k

20

should be small, but k can be larger, eg $k=3$ or $k=4$ to further reduce undesirable crosstalk disturbances, but at the penalty of less efficient use of the bandwidth.

The FWM power P_{ijk} , generated by three continuous wave channels of input powers P_i , P_j , P_k at frequencies f_i , f_j , and f_k at the output of a fibre with attenuation α and length z is

$$P_{ijk} = d_{ijk}^2 \gamma^2 L_{eff}^2 P_i P_j P_k \eta_{ijk} e^{-\alpha z} \quad (1)$$

where d_{ijk} is the degeneracy factor, taking value 1 or 2 for degenerate and non degenerate terms, respectively, γ the non-linear coefficient, L_{eff} the effective length, and η_{ijk} the efficiency, which can be approximated for long enough NZDSFs as $\eta_{ijk} \equiv \alpha^2 / \Delta \beta_{ijk}^2$. The phase matching coefficient $\Delta \beta_{ijk}$, away from the zero dispersion region, is

$$\Delta \beta_{ijk} = \frac{2\pi c}{\lambda_0^2} D_c \Delta \lambda_{ik} \Delta \lambda_{jk} \quad (2)$$

where D_c is the fibre dispersion and $\Delta \lambda_{ik}$ and $\Delta \lambda_{jk}$ are the wavelength spacing between channels i and k , and j and k . In the case of channels arranged on the ITU grid, $\Delta \beta_{ijk}$ takes the discrete values:

$$\Delta \beta_n = n \left(\frac{2\pi c}{\lambda_0^2} \right) D_c \Delta \lambda^2 \quad (3)$$

and thus also the efficiency becomes $\eta_n = \eta(\Delta \beta_n)$, where $n = |i-k||j-k|$ is the efficiency order, and $\Delta \lambda$ is the selected ITU grid resolution, typically a multiple of 0.4 nm.

Figure 3 shows one group of three wavelengths in more detail placed on an equal space grid at slots 1, 3 and 4.

A slot corresponds to the selected grid resolution $\Delta\lambda$. In Figure 3, all FWM terms are also summarised. Each term is represented by the indices ijk of the three channels involved in the product. For instance, the term 134 falling on slot 0 labels the FWM contribution jointly generated by the channels at slots 1, 3 and 4. For each FWM term, the corresponding efficiency (ie relative magnitude) η_n is also marked in Figure 1. It will be seen that no FWM term falls on the three channels, and the efficiency of the FWM terms decreases with their distance from the "three channel group" composed of slots 1 through 4. The invention adds more channels to the WDM comb by repeating as many three-channel groups as needed, spaced k slots apart from each other as shown in Figure 2. The bandwidth occupied by an N-channel WDM system is therefore

$$B = [4Q + k(Q-1) + (k+R)\min(1, R)]\Delta\lambda \quad (4)$$

15

where Q and R are the quotient and the remainder of the division of N by 3, namely $N=3Q+R$. Note that the in-band FWM terms falling on a channel within a specific group appear because of the presence of channels belonging to different groups. Thus, by increasing the slot distance k between adjacent groups, the efficiency of the in-band FWM terms decreases, at the expense of an increase of the system bandwidth B . The fractional bandwidth expansion, defined as $\epsilon_B = B/(N\Delta\lambda) - 1$, can be found, for typically large values of N , as $\epsilon_B \equiv (k+1)/3$, and depends only on k . It is easy to verify that the smallest efficiency order n of the in-band FWM terms is 1 when $k = 0$, 4 when $k = 1$, and $n = k + 4$ for $k \geq 2$.

At low transmitted power levels, the equal channel spacing (ECS) is the best scheme, i.e., the one that minimises the system bandwidth. As the per channel power increases, the signal-to-crosstalk ratio (SXR) quickly decreases below a tolerable threshold value

5 SXR_{min} for some channels of the comb.

The resulting ECS system bandwidth, for a $N=32$ channel system, is plotted in solid line in Figure 4 versus the average input channel power. The low power grid resolution is 0.4 nm, increasing in steps of 0.4 nm at each discontinuity in the curve.

10

Figure 4 also shows the system bandwidth of the TCC schemes, for the same system and fibre parameters. Consider first the TCC with grid resolution 0.4 nm, dashed line. As the power increases, SXR_{min} is reached by some channels, and the island distance k is increased by one unit at each discontinuity, starting at low-power with $k=0$. Up to

15 average input power per channel $P_{in} = -1$ dBm the ECS is the best scheme. For higher power values, up to about 9 dBm, the TCC with ITU grid resolution 0.4 nm is the most efficient in terms of system bandwidth.

However, as the island spacing k becomes large, even the TCC becomes inefficient, and

20 a way of recovering bandwidth efficiency is to opt a TCC scheme with a higher grid resolution, i.e., by enlarging the grid slots. The system bandwidth for the TCC scheme with resolution 0.8 nm is also shown in the Figure 4 in dotted line.

CLAIMS

1. An optical transmission system including an optical transmitter and an optical fibre, the transmitter being arranged to transmit along the fibre a plurality of optical channels each at a different wavelength placed on an equally spaced wavelength grid, the channels being organised into groups of three, each of which is placed on four adjacent grid positions, one position of which is unused, with adjacent groups being spaced apart from each other by two or more vacant grid positions.
2. An optical transmission system as claimed in Claim 1 and wherein the unused grid position in each group of three channels occurs at the second grid position for all groups.
3. An optical transmission system as claimed in Claim 1 and wherein the unused grid position in each group of three channels occurs at the third grid position for all groups.
4. An optical transmission system as claimed in any of the preceding claims and wherein all adjacent groups are spaced apart by two vacant grid positions.
5. An optical transmission system as claimed in any of the preceding claims and wherein the grid spacing is 0.4nm.
6. An optical transmission system as claimed in Claims 1 to 4 and wherein the grid spacing is 0.8 nm.

7. An optical transmission system as claimed in any of the preceding claims and wherein sixteen or more optical channels are provided.

8. An optical transmission system in which the optical fibre is a non-zero dispersion fibre.

Applicant's or agent's file reference MNI-16SPC	International Application No. PCT/US01/19464
--	--

**INDICATIONS RELATING TO DEPOSITED MICRO-ORGANISM
OR OTHER BIOLOGICAL MATERIAL**

(PCT Rule 13bis)

<p>A. The indications made below relate to the deposited micro-organisms or other biological material referred to in the description at the instance "_____" on: page 2, line 19; page 12, line 25; page 14, line 1; page 14, lines 37; page 15, line 3; page 15, line 10; page 15, line 13; page 15, line 35; page 15, line 38; page 16, line 3; page 16, line 5; page 16, line 13; page 16, line 20; page 16, line 23; page 16, line 35; page 16, line 36; page 16, line 36; page 17, line 2; page 17, line 27; page 17, line 36; page 18, line 2; page 18, line 7; page 18, line 28; page 19, line 17; page 19, line 22; page 20, line 1; page 21, line 16; page 21, line 21; page 22, line 5; page 22, line 8; page 22, line 26; page 25, line 3; page 28, line 32; page 28, line 36; page 43, line 10; page 67, line 2, and the second "_____" on page 85, line 21</p>	
<p>B. IDENTIFICATION OF DEPOSIT Further deposits are identified on an additional sheet. <input type="checkbox"/></p>	
<p>Name of depositary institution American Type Culture Collection (ATCC)</p>	
<p>Address of depositary institution (including postal code and country) 10801 University Boulevard, Manassas, VA 20110-2209 USA</p>	
<p>Date of deposit 01 June 2001 Accession Number PTA-3426</p>	
<p>C. ADDITIONAL INDICATIONS (leave blank if not applicable) This information is continued on an additional sheet. <input type="checkbox"/></p>	
<p>D. DESIGNATED STATES FOR WHICH INDICATIONS ARE MADE (if the indications are not for all designated States)</p>	
<p>E. SEPARATE FURNISHING OF INDICATIONS (leave blank if not applicable)</p>	
<p>The indications listed below will be submitted to the International Bureau later (specify the general nature of the indications, e.g., "Accession Number of Deposit")</p>	

<p>For Receiving Office use only</p> <p>This sheet was received with the International Application</p> <p>Authorized Officer</p>	<p>For International Bureau use only</p> <p>This sheet was received by the International Bureau on.</p> <p align="center">15 OCTOBER 2001</p> <p>Authorized Officer</p> <p align="center"><i>[Signature]</i></p>
--	---

1/2

Fig.1.

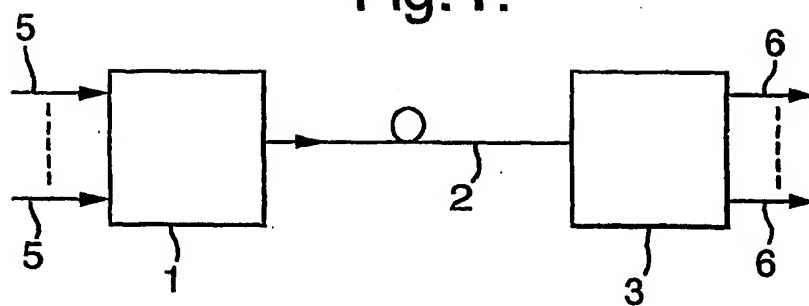
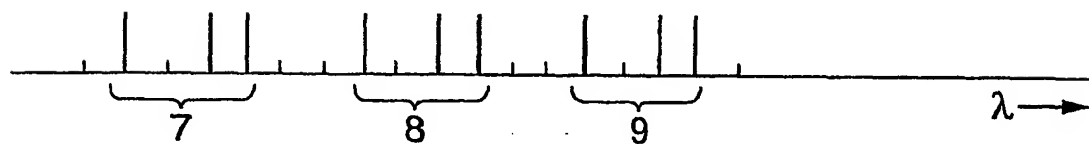


Fig.2.



2/2

Fig.3.

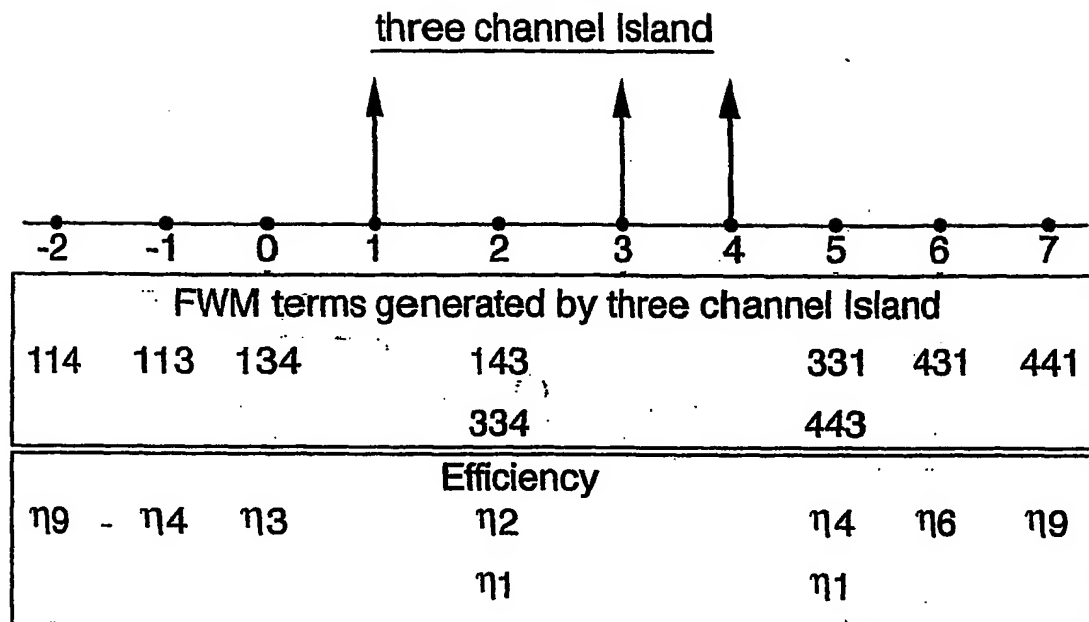
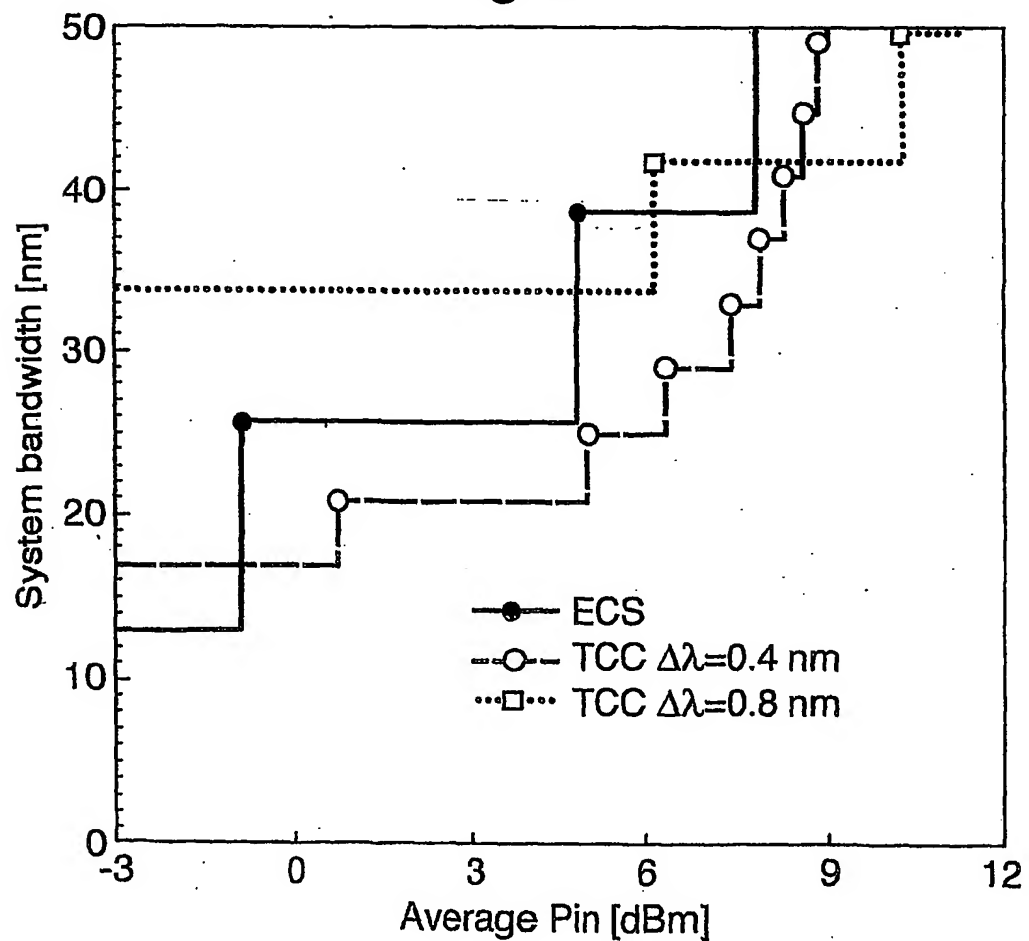


Fig.4.



A. CLASSIFICATION OF SUBJECT MATTER
 IPC 7 H04J14/02 H04B10/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H04J H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 00 31910 A (CIENA CORP) 2 June 2000 (2000-06-02) page 1, line 4 - line 5 page 2, line 4 - line 5 page 8, line 17 - page 9, line 12; figure 2 page 11, line 4 - page 12, line 13; figures 5-7 --- -/--	1, 4-8

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents:

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- *Z* document member of the same patent family

Date of the actual completion of the international search

15 January 2002

Date of mailing of the international search report

25/01/2002

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
 NL - 2280 HV Rijswijk
 Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
 Fax: (+31-70) 340-3016

Authorized officer

Roldán Andrade, J

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SARDESAI, H. P. ET AL: "SIMPLE CHANNEL PLAN TO REDUCE EFFECTS OF NONLINEARITIES IN DENSE WDM SYSTEMS" SUMMARIES OF PAPERS PRESENTED AT THE CONFERENCE ON LASERS AND ELECTRO-OPTICS. CLEO 99. TECHNICAL DIGEST. POSTCONFERENCE EDITION. BALTIMORE, MD, MAY 23 - 28, 1999, CONFERENCE ON LASERS AND ELECTRO-OPTICS, NEW YORK, NY: IEEE, US, 1999, pages 183-184, XP000901211 ISBN: 0-7803-5658-6	8
A	page 183, left-hand column, paragraph 1 page 183, middle column, paragraph 2 -right-hand column, paragraph 1; figure 3A	1-7
A	EP 0 880 249 A (NIPPON ELECTRIC CO) 25 November 1998 (1998-11-25) column 1, line 3 - line 7 column 4, line 21 -column 5, line 7; figures 4A,4B,4C,5,6	1-8

Patent document cited in search report		Publication date		Patent family member(s)	Publication date
WO 0031910	A	02-06-2000	EP	1133847 A1	19-09-2001
			WO	0031910 A1	02-06-2000
EP 0880249	A	25-11-1998	JP	3233269 B2	26-11-2001
			JP	10322314 A	04-12-1998
			EP	0880249 A2	25-11-1998

FWM Crosstalk Suppression Using Wavelength Grouping in 25-GHz-Spaced 10-Gbps-Based WDM Transmission Over NZ-DSF in C-Band

T. Katagiri, T. Naito, A. Miura, K. Amemiya, *Fujitsu Laboratories LTD., Kawasaki, Japan*;
R. Funane, *Fujitsu Higashi-Nihon Digital Technology Limited, Sapporo, Japan*, Email: toruk@labs.fujitsu.com.

We have proposed a novel wavelength grouping method which effectively suppresses FWM crosstalk with a minimum sacrifice in transmission capacity. A 1.36-Tbps WDM transmission employing this method was demonstrated over an enhanced LEAF in the C-band.

1. Introduction

A 25-GHz channel-spaced 10-Gbps-based dense WDM transmission system is an attractive way to meet the demand for higher transmission capacity caused by the growth in data traffic because its capacity (i.e., spectral efficiency) is equivalent to that of a 40-Gbps-based 100-GHz-channel-spaced WDM system. Transmission experiments at 25 GHz using SMF in both the C- and L-bands and NZ-DSF in the L-band [1, 2] demonstrated that the chromatic dispersion of fibers is large (more than 7 ps/nm/km) enough to suppress FWM crosstalk and thus achieve good transmission performance. The chromatic dispersion of NZ-DSF in the C-band is small, so FWM crosstalk is the limiting factor for a terrestrial system with a large span loss, resulting in degraded transmission performance. To overcome this weakness, the use of unequally spaced channels has been proposed [3]. It is, however, difficult for this system to construct a multiplexer and demultiplexer, for example, an arrayed waveguide grating (AWG). In this paper, we have proposed and demonstrated a method for suppressing FWM crosstalk that uses wavelength grouping (WG) for equally spaced channels to improve the transmission performance of a 25-GHz channel-spaced 10-Gbps-based dense WDM transmission system.

2. Wavelength Grouping to reduce FWM crosstalk

Wavelength allocation without and with WG in a WDM system with 25-GHz channel spacing is illustrated in Figure 1. The (m,n), where m and n = {1, 2, 3, ...}, represent the type of WG: m is the number of continuous signal wavelengths with the lightwave source "on", and n is the number of signal wavelengths next to them with the lightwave source "off". The crosstalk due to FWM is more and more suppressed by WG as the number of combinations of signal wavelengths that contributes to FWM generation decreases [4]. The wavelength allocation to achieve the WG is selected in order to reduce the target of the FWM crosstalk to less than -25.5 dB corresponding to 1-dB Q-penalty as OSNR = 16.8 dB with a conventional FEC.

Figure 2 shows the FWM crosstalk versus the signal wavelength for 100-km enhanced LEAF transmission in the C-band with continuous lightwaves (i.e., non-modulated signals). The experimental and calculated results are almost the same without and with WG. Figure 3 shows the FWM crosstalk suppression versus m, with n=1. When m was small, FWM crosstalk was greatly suppressed, the transmission distance was extended, and the transmission capacity was reduced. When m was large, the FWM crosstalk was little suppressed, the transmission distance was limited, and the transmission capacity was somewhat reduced. There is thus a trade-off between transmission capacity and distance. We can design the number of m, considering the required FWM crosstalk based on the calculated results as shown in Figure 3.

3. Experiment

As shown in Figure 4, we used a transmitter with 160 laser diodes (LDs) with wavelengths from 1530.33 nm to 1562.03 nm as the 25-GHz-spaced

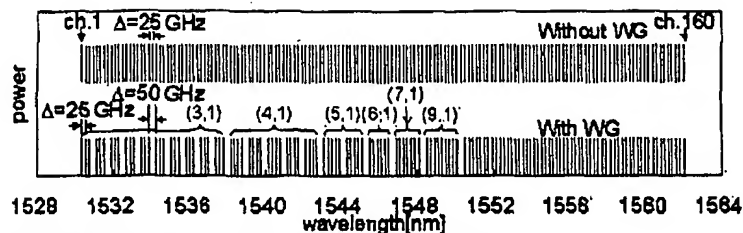


Figure 1. Wavelength allocation for the wavelength grouping (WG).

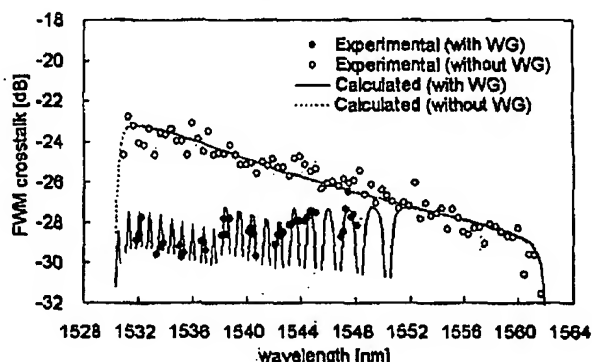


Figure 2. Characteristics of FWM crosstalk.

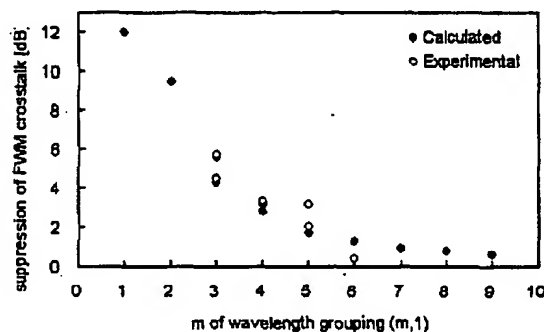


Figure 3. Characteristics of FWM crosstalk suppression.

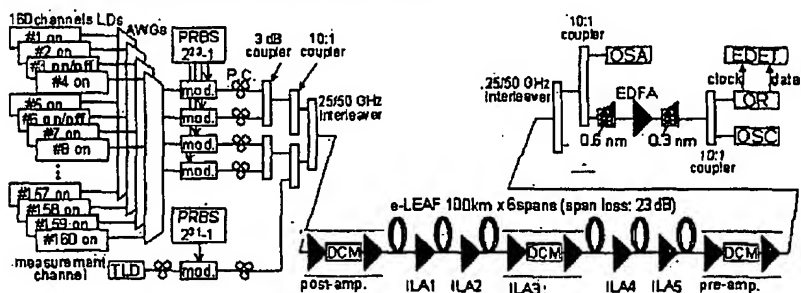


Figure 4. Experimental setup.

WDM signal source. Each was multiplexed with 100-GHz spacing using four AWGs. Each 100-GHz-spaced WDM signal and the measurement signal were modulated with LiNbO₃ Mach Zehnder (MZ) modulators with NRZ 9.95 Gbps and a PRBS of 2³¹-1 and 2³¹-1. Each channel had a random state of polarization because there was no polarization-maintaining fiber after the MZ modulators. Polarization controllers were located at each modulator's output because the polarizations for adjacent channels were so controlled as to measure the worst-case BER. The 25-GHz-spaced WDM signal was launched into the transmission fiber through couplers, a 25-GHz/50-GHz interleaver, and a post-amplifier consisting of a

two-state EDFA. The fiber input power for each span was -3 dBm/ch. The transmission line consisted of six spans with a 100-km enhanced LEAF per span (span loss: 23 dB, chromatic dispersion: +440 ps/nm) and five in-line amplifiers with a two-state EDFA. On the receiver side, the received signal was selected through a pre-amplifier, a 25-GHz/50-GHz interleaver, and cascaded tunable filters with 0.6- and 0.3-nm FWHM. Dispersion compensation modules were installed in the post-amplifier, pre-amplifier and in-line amplifier after the third span (ILA3). The LDs of the channels listed in Table 1 were turned off to achieve WG. We selected the channel numbers taking into account the experimental results of FWM crosstalk without WG. The

use of WG reduced the transmission capacity from 1.6 Tbps (10 Gbps \times 160 channels) to 1.36 Tbps (10 Gbps \times 136 channels).

Channels (total 24)	3, 6, 9, 12, 15, 18, 22, 27, 34, 41, 48, 54, 59, 64, 68, 72, 76, 80, 84, 88, 92, 96, 100, 104
------------------------	---

Table 1. Channels of signal off to achieve a wavelength grouping (WG).

Figures 5(a) and (b) show the received spectra after 600-km transmission. The 24 signal wavelengths were turned off in the case of WG, as shown in Figure 5(b). The received OSNRs for all channels were 16.8 dB, and the received power deviation was less than 6 dB without and with WG.

Figure 6 shows the FWM crosstalk for all channels after 600-km transmission, measured under the worst-case BER. The wavelength dependence of the crosstalk characteristics was not same as that after 100-km transmission, shown in Figure 2, because of FWM resonance in multi-span dispersion-managed link [5]. The reduction in FWM crosstalk on average was 4.8 dB that was almost the same as Figure 3, from -23.2 to -28.0 dB, around 1546 nm with (3,1) WG.

Figure 7 shows the Q-factors for all channels, which were converted from the measured BERs after 600-km transmission under the same conditions as for measurement of FWM crosstalk. The worst Q-factor was improved by 3 dB, from 11.8 to 14.8 dB. This improvement can extend the transmission distance by 40%. The Q-factor deviation of each channel with WG was smaller than that without WG. The received waveforms of 1532.29 nm (11-th channel) without and with WG (the insets of Figure 7) show clearly that the proposed method improved waveform distortion.

Figure 8 shows the relationship between FWM crosstalk and the Q-penalty, which is the difference between the back-to-back and received Q-factors. The experimental and calculated results were almost the same. As FWM crosstalk was suppressed from -20.5 to -25.8 dB with (2,1) WG, which reduced the Q-penalty by at least 2 dB. An additional penalty was measured when FWM crosstalk was large because of nonlinear effects such as XPM.

We measured the time-dependence characteristic of the Q-factor for six hours to investigate the validity of the measurement method. Measuring the worst case FWM crosstalk was sufficient because the Q-factor at the initial setting was almost the same as the worst one in 360 points. The average of Q-factor was 15.0 dB, and the standard deviation of Q-factor was 0.18 dB.

4. Conclusion

Using wavelength grouping, FWM crosstalk have been reduced in 25-GHz-spaced 10-Gbps-based WDM transmission over 100 km \times 6 enhanced LEAF in the C-band. FWM crosstalk was reduced from -20.5 to -25.8 dB, and the Q-factor was improved by at least 2 dB with (2,1) wavelength grouping. The transmission distance was extended by 40%, while the transmission capacity was reduced by only 15%. This proposed method is thus useful for 25-GHz-spaced dense WDM transmission using a low chromatic dispersion fiber.

Acknowledgement

We thank Takeshi Hoshida, Kaori Yamada, Hideyuki Minami, Hideyuki Miyata, Kazuo Yamane and Hiroshi Onaka for their advice and encouragement.

References

- [1] C. Hullin, et al., ECOC 2002, 1.1.3.
- [2] A. K. Srivastava et al, OFC 2000, PD 27.
- [3] F. Forghieri, et al., IEEE J. Lightwave Technol., Vol. 13, No. 5, pp. 889 - 897, May 1995.
- [4] K. Inoue, et al., IEEE J. Lightwave Technol., Vol. 13, No. 1, pp. 88 - 93, Jan 1995.
- [5] Ekaterina A. Golovchenko, et al., IEEE Photon. Technol. Lett., Vol. 10, No. 10, pp. 1481 - 1483, Oct. 1998.

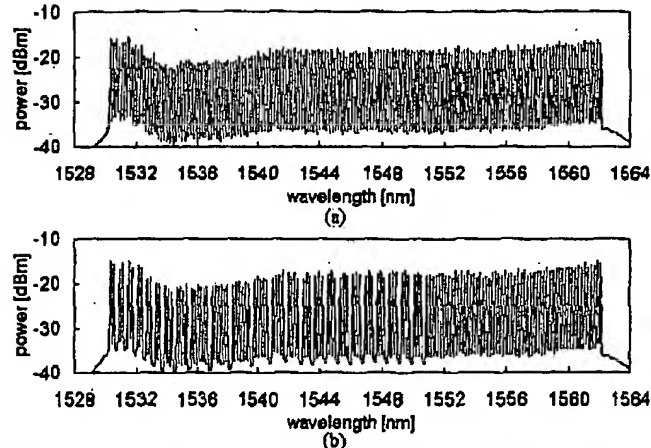


Figure 5. Received spectra after 600-km transmission (a) without the wavelength grouping (WG) (b) with WG.

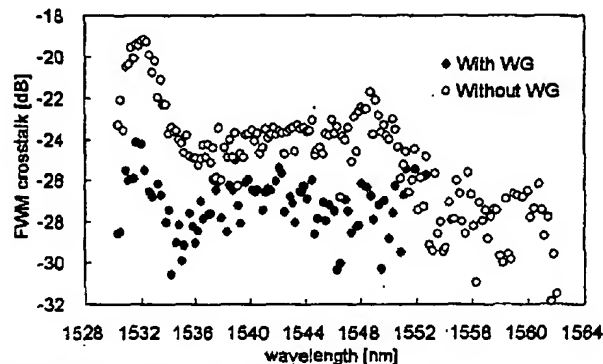


Figure 6. FWM crosstalk after 600-km transmission.

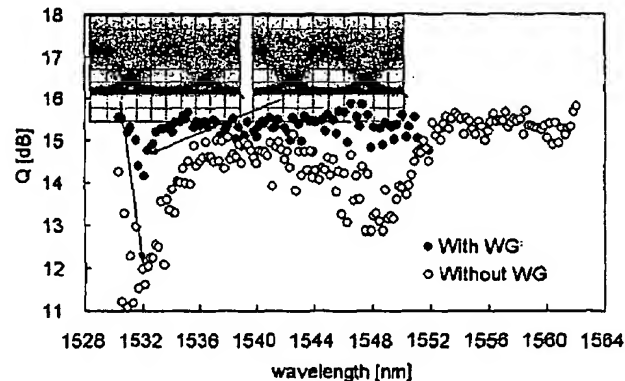


Figure 7. Q-factor after 600-km transmission.

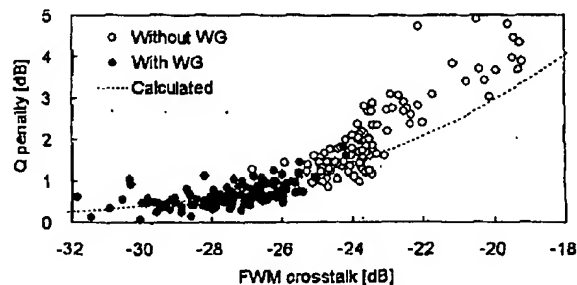


Figure 8. Q-penalty versus FWM crosstalk.